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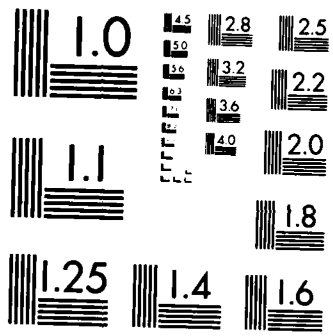

MICROCOPY RESOLUTION TEST CHART
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Program Engineering &
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Washington, D.C. 20591

AD A125689

Investigation of Hydrophobic Radomes for Microwave Landing System

A.W. Moeller
R.E. Willey

November 1982

Final Report

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16. Abstract

A variety of hydrophobic materials were tested to determine useful life and degree of effectiveness. The tests consisted of monitoring coated samples which were exposed to year-round weathering; field tests in which operating MLS radomes were coated and system accuracy measured; and an evaluation by a testing laboratory using a weatherometer. It was concluded that Teflon fabric offered the best compromise between effectiveness and maintainability, although fumed silicon dioxide provided the highest hydrophobicity.

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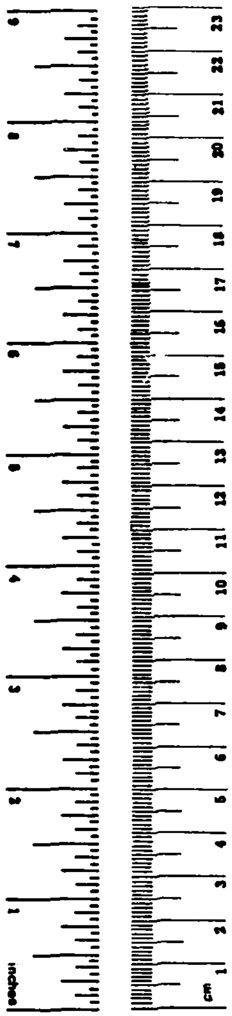
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

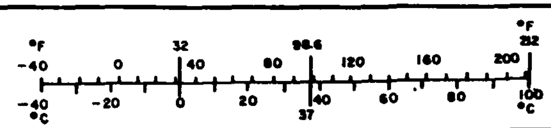
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

A series of tests made to evaluate the hydrophobic properties of various radome materials and coatings are described. The tests were made over a period of several years and included environmental weathering of test panels, field testing of radomes of operating MLS stations, and laboratory weatherometer testing of selected samples.

At the conclusion of this project, it was recommended that the outer surface of contemporary radomes be of Teflon fabric since this exhibited good hydrophobicity and required minimal maintenance procedures. It was also recommended that a recently developed primer and fumed silicon dioxide coating, which performed excellently based on weatherometer tests, be field tested and evaluated as a potential replacement for the Teflon fabric.

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1. INTRODUCTION

The radomes used on MLS and other antenna systems are designed to achieve low signal attenuation and to minimally effect beam shape and pointing accuracy. While these qualities are generally achieved through careful design of the radomes, they are degraded by the presence of moisture adhereing to the radome surface. In particular, the situation is recognized as being particularly troublesome if the moisture forms a continuous film or laminar flow of water across significant areas of the radome surface as opposed to rivulets or discrete droplets on the surface. The phenomenon is not new, having been recognized for many years. Experience with the various MLS antennas tested over the past ten years has repeatedly verified the presence of the problem, and the stringency of the accuracy specification is such that moisture accumulation sometimes drives the antenna performance past monitor limits, causing the system to shut down.

Reduction of surface wetting, causing the water to bead and roll off the surface, is a common phenomenon readily observable with many types of protective coatings such as waxes and oily compounds. Such repellancy (hydrophobicity) does not last due to hydrolizing of the surface interface and/or the accumulation of airborne and water-borne debris. Typically, hydrophobic coatings will create a contact angle of 90 degrees or less (contact angle is the dihedral angle, measured in the liquid, at the solid-liquid interface). As the contact angle increases, the solid-liquid interface area is reduced and the hydrophobicity increases. When the contact angle exceeds about 135 degrees, the surface is said to be superhydrophbic.

In 1972, a material called hydrophobic fumed silica was developed. In appearance it is an extremely fine powder 0.1 to 0.5 microns in size. One gram of this material has a surface area of approximately 400 square meters. When applied to a surface, this material exhibits superhydrophobicity; the nonwettability of the particles combined with the surface roughness and the viscosity of

water virtually eliminates intimate water contact with the surface. The hydrophobic fumed silicon is patented, manufactured and sold by Tulco, Inc., N. Bellinica, MA. under the trade name Tullannox. In addition, several coatings were developed in liquid form by Tulco, Inc. and Silibond Products, Inc. of Wilmington, MA. called Tullannox L.C. 410 and Silibond 1828-3A, respectively. Although both products exhibited superhydrophobicity, durability remained a problem.

In 1976 a new product called Vellox 140 was developed by the Clifford W. Estes Co. of Lyndhurst, N. J. It incorporated the hydrophobic silica in a two-part system consisting of a primer and a top coat. The primer served as a bonding interface to which the hydrophobic silica in a liquid suspension adhered when sprayed. Bonding was achieved by both mechanical and chemical means. Vellox 140 exhibited substantially improved durability. The earlier products (Tullannox 400 and Silibond 1828-3A) were single-coat systems and available also in aerosol cans.

Bendix recognized the need to solve the water film problem and realized that the fumed silica offered a possible solution. Accordingly, an in-house effort was initiated several years ago to investigate this problem.

The success of this limited effort contributed to the FAA decision to expand and continue the effort and to include evaluation of MLS antennas in the field. In the interest of presenting a complete and coherent summary of the progress to date, the results of the tests performed by Bendix prior to this contract are included.

The basic purpose of this funded study is to find a suitable material (or combination of materials) to achieve immunity from the effects of the presence of moisture* on the radome surface.

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* "Moisture" means water in either the liquid or solid state, i.e., droplets, fine mist, ice, snow, etc.

The Statement of Work breaks this down into four tasks, which are paraphrased below:

(1) Evaluate the various materials and hydrophobic coatings presently in use, including life expectancy and field maintenance.

(2) Test the various candidate materials to determine hydrophobic properties, adhesiveness, weathering, and effect of ultra violet (uv) exposure.

(3) Select preferred technique(s) in collaboration with the Contracting Officer.

(4) Procure and install radomes employing the selected technique at appropriate field sites, monitor the performance, and collect and evaluate the data, culminating in a recommendation for the best approach.

Under Task 1 (Section 2 of this report), we evaluated materials currently in use. This was accomplished by (a) evaluation of data available from books, articles, etc., (b) evaluation of studies previously performed by Bendix under the various test samples, and (c) observing treated radomes on MLS antennas in the field. Our evaluation generally addressed service life and water-shedding effectiveness.

Section 3 of this report deals with Task 2, where a chemical firm under subcontract to Bendix performed tests to quantify the various specified properties. The subcontractor report is included as Addendum A to this report. Some RF testing was performed on the antenna range; this data is also included in Section 3.

Section 4 summarizes the results and presents recommendations for future work.

2. MATERIAL EVAULATION

2.1 PROSPECTIVE MATERIALS

In selecting candidate materials for the Bendix test, both the base material (radome) and the hydrophobic coating had to be considered because of the possible dependency of coating life upon the base material and the application technique. Of greatest interest were materials that were similar to those used on MLS antennas already in the field. The materials selected for evaluation were

- o Flat fiberglass panel
- o Conolite membrane with Tedlar covering
- o Duroid (Teflon, fiberglass)

and are identical or similar to the radomes used on the Bendix Small Community, Basic Narrow, and Basic Wide MLS installations.

The hydrophobic materials included Teflon based compounds and fumed silicon dioxide. The Teflon based materials include Teflon TFE, Teflon FEP-200, fluorocarbon spray, Tefzel 100 LZ, and PVF (Tedlar). Materials using fumed silicon dioxide as a base are Fusidox, Vellox, Silibond, and Tullannox. A complete description of these materials is given in Table 2-16 at the end of this section.

One other product, HMOD-4, has been considered; it was developed for use on aircraft windshields to repel water so that visibility can be maintained. This material is somewhat oily to the touch, so it does not clearly fit in the three categories just defined.

The previously mentioned materials are intended for use on the exterior surface of the radome and are applied over the structural fabric of the radome. The most common radome base material considered was fiberglass composite, using various types of matrix materials (polyester, epoxy, Teflon, Tefzel, etc.). In some cases, a thin film of an ultraviolet resistant material, such as Tedlar, was laminated to the outer surface (such surfaces are often etched to promote bondability.)

2.2 APPROACH

2.2.1 LITERATURE SEARCH

Initially, a search was made of available technical articles, books, papers, etc. The technical articles which were located covered the documentation of difficulties encountered as a result of precipitation (principally rainfall) and of various measures applied to increase the water repellency of various radomes. The documents considered in the study are listed in Section 2.3. The work encompassed by these studies generally spanned the time frame of 1965 through 1979.

2.2.2 MATERIAL TESTING

Next, Bendix proceeded to solicit information and samples from suppliers of the various materials recognized as having hydrophobic properties. Miscellaneous testing was performed on these samples, both in the lab and outdoors on the antenna range.

2.2.3 FIELD TESTING

Those materials that showed promise were then applied to MLS radomes in the field at airport sites. Testing was limited to those coating materials that could readily be applied outdoors by spray or brushing techniques. The MLS antenna radomes (with one exception) are plane vertical surfaces. The one exception is a half-cylinder type with the axis of the cylinder being vertical.

Various radome constructions are utilized. One type is of sandwich construction - two fiberglass skins separated by a honeycomb core, about 5/8 inch thick. This type includes a pattern of horizontal heating wires for deicing. A second type utilizes a single stretched membrane, a polyester/fiberglass material marketed as "Conolite", .010-inch thick, with a .001-inch layer of DuPont "Tedlar" laminated to the outside surface. A third type (used for the half-cylinder radome) is laid-up fiberglass, with a white gelcoat exterior, .030" to .040" thick, with a pattern of heating wires.

In addition to the scanning beam antenna radomes, the field monitors were also subjected to materials tests. Two general types were in use: 1) a horn type, the mouth of which was covered with 1/16-inch Teflon-figerblass board material (Rogers Duroid 5870), with a serpentine pattern of horizontal heating wires on the inside surface, and 2) a slotted waveguide unit (C-band waveguide, about 2 feet in length) covered with a Teflon shrink tube.

The radome characteristics are summarized in Table 2-1.

2.3 LITERATURE RESEARCH

The documents judged to be of most interest to this study are listed below. In general, the articles corroborated our observations regarding the degradation of wet radome surfaces and documented early experiments regarding water-repellent surfaces.

(1) Losses Due To Rain On Radomes and Antenna Reflecting Surfaces, B. C. Blevis, IEEE Transactions on Antennas and Propagation, January 1965.

(2) More On Wet Radomes, J. Ruze, IEEE Transactions on Antennas and Propagation, Sept. 1965.

(3) O'Hare ASDE-2 Radome Performance in Rain; Analysis and Improvement, R. M. Weigand, FAA Report No. FAA-RD-73-22, March 1973.

(4) Performance of a Water-Repellent Radome Coating In An Airport Surveillance Radar, R. M. Weigand, Proceedings of the IEE, August 1973.

(5) Measurements of 20 GHz Transmission Through A Radome In Rain, I. Anderson, IEEE Transactions on Antennas and Propagation, Sept. 1975.

(6) The Role of Rain in Satellite Communications, D.C. Hogg and Ta-Shing Chu, Proceedings of the IEEE, Sept. 1975.

(7) Preliminary Testing of Teflon As A Hydrophobic Coating for Microwave Radomes, C.A. Siller, Jr., IEEE Transactions on Antennas and Propagation, July 1979.

TABLE 2-1. RADOMES UNDER TEST

SYSTEM LOCATION	RADOME	SIZE	ORIENTATION
MLS BASIC NARROW WASHINGTON NATIONAL RUNWAY 18	Fiberglass flat sandwich (AZ)	5 ft x 9 ft	North
	Fiberglass half cylinder (EL)	8 ft x 1 ft	North
	Flat Duroid sheet (Field Mon.)	1 ft x 1 ft	South
MLS SMALL COMMUNITY WASHINGTON NATIONAL RUNWAY 33	Fiberglass flat sandwich (AZ)	5 ft x 9 ft	SSE
	Fiberglass half cylinder (EL)	6 ft x 1 ft	SSE
	Flat Duroid sheet (Field Mon.)	1 ft x 1 ft	NNW
MLS BASIC WIDE NASA WALLOPS RUNWAY 22	Conolite/Tedlar stretched membrane (AZ)	5 ft x 13 ft	NE
	Fiberglass flat sandwich (EL)	1.5ft x 13ft	NE
	Teflon shrink tubing (Field Mon.)	1 in x 2 ft	SW

(8) Hydrophobic Coating for Antenna Weather Windows, H. Hoffman, Microwave Journal, Oct. 1979.

Reference 1 includes test data at 3.65 GHz (close to the 5 GHz MLS operating frequency) and states that a thin (.005 inch) water film resulted in a 1.1 dB transmission loss; for .010 inch, 2.6 dB; for .015 inch, 4.2 dB; for .020 inch, 5.6 dB. These numbers give an indication of the severity of the effect. Reference 2 confirms the conclusions of Reference 1, and indicates a sensitivity to polarization as a function of angle of incidence.

Reference 3 is a comprehensive report on the ASDE-2 radar at O'Hare Airport, a geodesic dome over a K-band (24 GHz) radar, and therefore of limited applicability to the MLS application. However, this investigation probed into the performance of the same general group of hydrophobic materials that Bendix has been considering, and it gives an indication of what problems we can expect. While fumed silicon dioxide was singled out as the best performer, HMOD-4 was ultimately chosen because of a requirement to maintain visual clarity through the transparent LEXAN radome panels. The illustrations showing before/after performance under heavy rain are very striking (at K-band, however, the effects of a wet radome are considerably worse than for C-band). Reference 4 deals with the same subject and expands upon it. It singles out accumulated grime as a major factor in derogating the performance of the hydrophobic coatings.

Reference 5 was interesting in that the radome material was quite similar to the materials in use on some of the MLS antennas, a 0.30" fiberglass material with an outer layer of Tedlar laminated to it. However, the radome simulated a 90-foot dome, and the frequency was 20 GHz. The conclusion was that maintenance of a non-wetting surface is an essential requirement. It was reiterated that grime is a big factor regarding wettability; also, a drainage flow in rivulets, rather than sheet type flow, was much preferable. Dry snow and ice caused little transmission loss, but the same covering, when in the melting process, caused much greater effects.

Reference 6 deals principally with rain and its effects on the signal in space, but one section does touch on the wet radome situation. The concern expressed in this article is so great that the recommendation is made to utilize antennas (for satellite communications) without radomes. Also, it is suggested that rivulet flow in a hydrophobic radome may introduce aperture phase errors and cross polarization effects.

Reference 7 considers Teflon as a hydrophobic radome surface and compares it with fumed silicon dioxide and HMOD-4. Transmission loss is measured at 18.7 GHz, where fumed silicon dioxide again shows up as the best performer when new; HMOD-4 is next in order and Teflon TFE performs almost as well. However, the writer states that fumed silicon dioxide can completely fail within three weeks, while HMOD-4 was excellent after a fifteen-month exposure. He reports also that the Teflon samples performed satisfactorily after a 15-month exposure. He concludes that Teflon offers excellent repellency and offers promise of extremely long durability in unprotected outdoor exposure (however, he does not address the problem of adhering the Teflon film to the base radome material where U.V. exposure tends to degrade the adhesive).

Reference 8 addresses tests of the hydrophobicity of a coated Mylar radome as a function of weather exposure, the radome covering the feed horn (4 inch by 5 inch) of a seven-meter antenna, at 19 and 28 GHz. Coatings representing silicones, Teflon, and vegetable type lubricants were abandoned in early testing because they had not weathered well. Products identified as FUSIDOX and SILIBOND 1828-3A weathered well, by comparison, and were subjected to further testing, with results indicating the life of FUSIDOX to be 2 to 4 weeks and SILIBOND 6 weeks. Also, the report describes some hydrophobicity remaining after more than a year of exposure with a SILIBOND coating.

These references deal generally with studies of the same materials presently under consideration by Bendix for use on MLS. However, most all these studies utilize test set-ups at much

higher frequencies than MLS so that the results are not directly applicable. None of these set-ups dealt with a phased array where a wide range of angles of incidence are encountered. Also, since the time period of the subject tests, improved formulations of some of the more promising coatings have been developed.

2.4 MATERIALS TESTING

In May 1979, the Bendix Communciations Division initiated an in-house test program to identify prospective candidate materials for further evaluation, development, and testing.

These tests, in general, were performed upon sample base material sections (approximately 10" x 10") coated with a hydrophobic compound and exposed to the elements on the Bendix antenna range. In a test such as this, the degree of water shedding capability is a subjective measurement, so that slight differences in perceived capability are not significant. Test samples were mounted on a vertical wall, facing south.

The coatings and base materials subjected to testing are shown in Table 2-2, with the tested combinations identified. Similar tests as reported by various other organizations (sources listed in the technical references, Section 2.3) are listed in Table 2-3. The chronology of testing can be seen in Table 2-4; note that some of the test samples were under test for as long as a year and a half.

Six samples were kept as controls and references for the entire duration of the test. These were stored indoors and away from UV exposure. These samples and their initial ratings are:

- o EFG board + 0.002" Teflon (Fair)
- o EFG Board + Vellox 140 (primer and sprayed top coat) (Excellent)
- o EFG board + Vellox (primer and wiped-on top coat with a rag) (Excellent)
- o EFG board + Fluorocarbon spray (Fair)
- o TFG board + AFC HMOD-4 (Good)
- o TFG board + Vellox (primer and sprayed top coat) (Excellent)

TABLE 2-2. COMBINATIONS OF BASE MATERIALS AND COATINGS TESTED BY BENDIX ENGINEERING

BASE MATERIAL \ COATING →	UNCOATED	VELLOX 140+048 PRIMER	LOCKHEED AFC HMOD-4	FLUOROCARBON SPRAY	TEFLON FEP 200	TEFZEL 200 LZ	VELLOX WHITE	VELLOX GREEN	VELLOX GRAY	VELLOX BLUE	SILIBOND 1828-4A
TFG Board		1									
EFG Board (dark)		10		2							
Conolite & Tedlar	5	9	3	4			11	12	13	14	15
EFG Board (light) & Tedlar					6						
EFG Board (light)	16					7					
Tefzel/ Glass fabric	8										

LEGEND: TFG - Teflon Fiberglass
EFG - Epoxy Fiberglass

NOTE: Numbers are for identification only

TABLE 2-3. COMBINATIONS OF BASE MATERIALS AND COATINGS TESTED BY REFERENCED SOURCES

COMBINATIONS OF BASE MATERIALS AND COATINGS TESTED BY REFERENCED SOURCES

BASE MATERIALS ↓ / COATINGS →	UNCOATED	FUMED SILICONE DIOXIDE	AFC H MODE-4	PASTE WAX	LIQUID WAX	PLASTIC POLISH	SILICONE FLUID	PVF (TEDLAR)	TEFLON BOARDS IN URETHANE BINDER	TEFLON TFE	SILIBOND 1828-3A	VEGETABLE LIKE LUBRICANTS	SILICONE	SOURCE OF DATA
.032 FIBERGLASS	X													
POLYCARBONATE (LEXAN)	X	X	X	X	X	X	X							REF 3
LAMINATED RADOME MEMBRANE								X						REF 5
.030 LAMINATE OF FIBERGLASS								X						REF 5
SOLID EPOXY / E-GLASS FIBERGLASS LAMINATE	X	X	X						X	X				REF 7
.002" MYLAR		X								X	X	X	X	REF 8

NOTE: SEE SECTION 2.3 FOR IDENTIFICATION OF REFERENCES

TABLE 2-4. CHRONOLOGY OF BENDIX TESTING

TEST* SAMPLE	1979	1980	1981
1	14Mo.		
2		22Mo.	
3		22Mo.	
4		22Mo.	
5		22Mo.	
6		19Mo.	
7		19Mo.	
8		19Mo.	
9		19Mo.	
10		19Mo.	
11		15Mo.	
12		15Mo.	
13		15Mo.	
14		15Mo.	
15		15Mo.	
16			7Mo.

Start of Contractual Effort

27-Month Total Time Span

*See Table 2-2 for identification of samples.

All of them retained their initial ratings with the exception of the fluorocarbon sprayed board, which changed to "Poor" in six months.

The 16 samples defined in Tables 2-2 and 2-4 were tested at intervals to determine their hydrophobicity. The testing consisted of spraying water on the surface and rating the water-shedding capability as excellent, good, fair, or poor, according to the following reference coatings:

Excellent - equivalent to fresh coat of Vellox 140

Good - equivalent to fresh coat of AFC HMOD-4

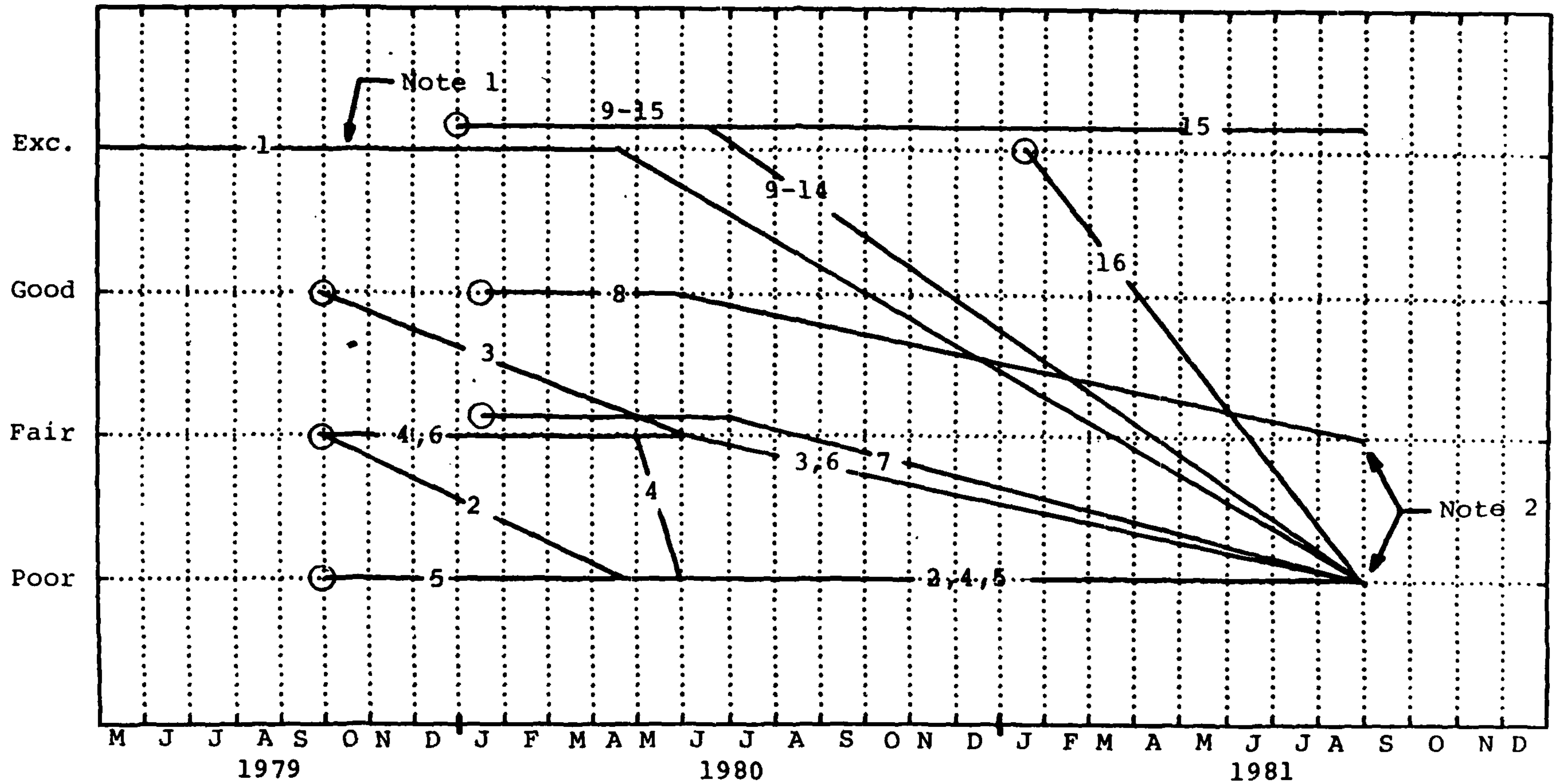
Fair - equivalent to clean Teflon surface

Poor - permitted water filming

These ratings were plotted over the time span of the test and are shown in Figure 2-1. The coating deterioration with time is vividly demonstrated here. In general, the coatings retain their initial properties for about six months before deterioration starts. The one exception is sample #15 - the Conolite/Tedlar membrane coated with Silibond. The reason for the relatively high and constant rating is not known at this time.

In addition to these time exposure tests, a snow and ice test was run in December 1980 and January 1981. Seven samples were prepared, and the effects of snow, frost, and ice on these samples are listed in Table 2-5. Samples #2 through #6 were inadvertently destroyed and were replaced by sample #7. Once again, the Conolite/Tedlar had better performance, both with Silibond and Vellox coatings.

In August 1981, the analysis was funded under the current contract, and a better orchestrated and coordinated effort was possible. Additional test panels were made and installed on a South-facing wall. Further, 5 samples were selected for more extensive testing, and four panels of each sample were mounted on retangular boxes whose sides faced the four cardinal directions. These sample panels are listed in Table 2-6. The performance of these samples is summarized in Table 2-7.



NOTE 1: Recoated left half with Vellox, right half with Silibond.

NOTE 2: Samples 6, 7, 8 cleaned with water and towel. Ratings increased to Fair for 6 and 7; no change for 8.

See Table 2.2 for sample identifications.

Figure 2-1. Hydrophobic Ratings of Bendix Test Samples

TABLE 2-5. SNOW/ICE TEST ON BENDIX SAMPLES

DATE	WEATHER	SAMPLE NO.* 1	2	3	4	5	6	7
24 Dec '80	Medium to heavy snow mixed with rain	ice crystals	clear	ice crystals	few icy droplets	ice crystals	patches of icy droplets	not tested
6 Jan '81	Frost	frost flowers	frost flowers	frost flowers	frost flowers	frost flowers	frost flowers	not tested
15 Jan '81	Wet snow, little wind	small beads of water		These samples were				clear
21 Jan '81	Snow preceded by freezing rain	consid. frost coating		overturned by the wind and destroyed. No				clear
22 Jan '81	Heavy frost	consid. frost coating		data is available.				some frost

*1. Uncoated Conolite
2. Conolite + 2 coats Silibond 1828-4A
3. Uncoated TFG
4. TFG + 1 coat Silibond 1828-4A
5. Uncoated Tedlar
6. Tedlar + coat Silibond 1828-4A
7. Conolite + Vellox S-048 Primer + 4 coats Vellox 140

TABLE 2-6. TEST SAMPLES AT BENDIX

PANEL NO.	PREPARATION DATE	BASE MATERIAL	SURFACE PREPARATION
1A	16 Nov '81	Conolite	Silibond 1828-4A, 1 coat sprayed
1B	16 Nov '81	Conolite	Silibond 1828-4A, 2 coats sprayed
2A	16 Nov '81	Conolite	Silibond 1828-4A, 3 coats sprayed
2B	16 Nov '81	Conolite	Silibond 1828-4A, 4 coats sprayed
3	16 Nov '81	Conolite	AFC-HMOD-4, 4 coats sprayed
4A	16 Nov '81	Conolite	Primer: Vellox ADZ07-A, brushed Finish: Vellox aersol, 1 coat
4B	16 Nov '81	Conolite	Primer: Same Finish: Vellox aerosol, 2 coats
5	16 Nov '81	CHR-10TB*	None
6	16 Nov '81	CHR-10TB*	AFC-HMOD4, 2 coats
7	16 Nov '81	CHEMFAB 100-20R*	None
8	16 Nov '81	CHEMFAB 100-20R*	AFC-HMOD4, 2 coats
9	16 Nov '81	CHEMFAB B141-R*	None
10		CHEMFAB B141-R*	AFC-HMOD4
11	27 Mar '82	Conolite	Primer: Vellox ADZ-07 Finish: Micro-fine FSD, 7 coats, sprayed
12	16 Nov '81	Conolite	Primer: Vellox S-048 Finish: Vellox, 8 coats, sprayed

TABLE 2-6. TEST SAMPLES AT BENDIX (CONT)

PANEL NO.	PREPARATION DATE	BASE MATERIAL	SURFACE PREPARATION
13	24 Mar '82	Conolite	Primer: Vellox S-048 Finish: Microfine FSD, 7 coats, sprayed
14	24 Mar '82	Conolite	Teflon film, C-TAPE-36
15	24 Mar '82	Conolite	Silibond 1828, 7 coats, sprayed
16	29 Apr '82	Conolite	Vellox BC-500, brushed
17	16 Nov '81	Conolite	Silibond 1828, 7 coats, aerosol
18	16 Nov '81	Conolite	Primer: Vellox #48 Finish: Microfine FSD, 7 coats, sprayed
19	16 Nov '81	Conolite	Primer: ADZ07 Finish: Microfine FSD, 7 coats, sprayed
20	16 Nov '81	CHEMFAB 100-10R	None
21	16 Nov '81	Teflon film C-TAPE-36	None

*CHR-10TB: Teflon Fabric
CHEMFAB 100-20R Teflon Fabrics manufactured by Birdair
CHEMFAB B141-R Structures Div., of Chemfab,
2015 Walden Avenue,
Buffalo, N.Y.

TABLE 2-7. EVALUATION OF BENDIX TEST SAMPLES**

SAMPLE	SURFACE COAT	DATE 26 Mar '82	13 Jul '82*	
1A	Silibond 1828-4A	2	3	
1B	Silibond 1828-4A	2	4	
2A	Silibond 1828-4A	2	5	
2B	Silibond 1828-4A	2	4	
3	AFC-HMOD-4	4	9	
4A	Vellox aerosol		3	9
4B	Vellox aerosol	3	9	
5	Teflon fabric	4	8 (3)	
6	AFC-HMOD-4 on Teflon fabric	4	8 (3)	
7	Teflon fabric	3	7 (2)	
8	AFC-HMOD-4 on Teflon fabric	3	7 (3)	
9	Teflon fabric	3	6	
10	AFC-HMOD-4 on Teflon fabric	3	7	
11	Micro-fine FSD	1	8	
12	Vellox 140		1	1
13	Micro-fine FSD	1	1	
14	Teflon film	3	6	
15	Silibond	1	2	
16	Vellox BC-500		-	7
17N	Conolite + Vellox 140 (7 coats aerosol)	1	-	
17E		1	-	
17S		1	3	
17W		1	3	
18N	Conolite + #48 primer & microfine Vellox 140 (7 coats aerosol)	2	2	
18E		1	3	
18S		2	2	
18W		1	2	
19N	Conolite + ADZ07 primer + microfine Vellox 140 (7 coats aerosol)	2	2	
19E		1	2	
19S		2	2	
19W		2	1	
20N	Chemfab 100-20R	3	5	
20E		3	5	
20S		3	4 (3)	
20W		3	4 (3)	
21N	Teflon film C-TAPE-36	3	4 (3)	
21E		3	4 (3)	
21S		3	4 (3)	
21W		3	4 (3)	

* Numbers in ( ) represent hydrophobicity after the panel was wiped with a dry cloth to remove accumulated surface dirt.
** Hydrophobicity is ranked from 1 (excellent) to 10 (extensive water sheeting present).

The real test of a coating is its performance in the field under actual operating conditions. The next section describes the results from applications at three MLS sites.

2.5 AIRPORT SITE TESTING

To expand upon the tests of material samples described previously, candidate materials were selected for field testing. These tests consisted of applying the sample materials to MLS radomes at Washington National Airport and NASA Wallops Flight Center.

After the start of the funded effort, the radomes at Washington National were recoated and test panels were emplaced (12 October 1981). The following two sections describe the radome tests and panel tests.

2.5.1 RADOME TESTS

Applications of the candidate coating materials were made,* and inspections were made at irregular intervals. Ideally, inspections would be made during or just after natural rainfall; more often, the inspecting engineer would splash or spray water on the radomes at various points and make observations as to the

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*At this time, it was concluded that Vellox 140 and Silibond 1828-4A showed the most promise; these items performed exceptionally well just after the initial application, and, although some previous data indicated a limited service life, the manufacturers were aggressively pursuing a program of development aimed at increasing the service life. Silibond, in particular, was supplied in aerosol spray cans, such that field application and repair were convenient. Both materials are based on fumed silicon dioxide. The differences arise in the means utilized to develop adhesion to the radome surface. Vellox requires a primer and a top coat and is applied with high pressure spray equipment; Silibond combines a binder resin with the Tullannox powder, all in one coat.

quality of the repellency. In many cases, partial reapplications ("touch-ups") were made just after the inspection to those areas where hydrophobic performance was much below standards. In a few cases, the system had been shut down by the monitoring subsystem, in which case a radome inspection would be conducted to determine the possible causes.

The following sections describe the observations made on the Basic Narrow and Small Community systems at Washington National and the Basic Wide system at NASA WFC. The Basic Narrow and Small Community systems were installed at Washington National about one year apart, the Basic Narrow in January 1979, and the Small Community in December 1980. The Basic Wide was installed at WFC in December 1979.

2.5.1.1 BASIC NARROW MLS

The initial material test used Vellox 140/ADZ07 on the Basic Narrow AZ and EL radomes at Washington National Airport on 4/14/79. The radomes were thoroughly cleaned, and the application performed per the manufacturer's instructions. The ADZ07 is a primer, slightly off-white in color so as to facilitate being able to tell where the material has been applied; the Vellox 140 top coat is a suspension of fumed silicon dioxide powder in solvent, and applications under high pressure cause a brief softening of the previously-applied primer in such a way that the fumed silicon dioxide powder sticks to the surface. Application in the field was less than ideal; windy conditions complicated the application and frequent problems occurred with the portable spray equipment. After application the hydrophobicity was rated as "excellent".

The first recorded inspection did not occur until six months later, at which time the hydrophobicity was rated generally good on both radomes, except that 70 percent of the AZ radome was reported as "good", and "poor" on the remaining 30 percent. Weeks later, the quality had degraded to "fair", and the radomes were recoated with Silibond 1828-4A (from spray cans). Thereafter, inspections

were conducted on a monthly basis, and frequent touch-ups were needed to maintain a reasonable degree of repellency. One system shutdown was reported as a part of this test on 6/3/80. The inspection/maintenance log is summarized in Table 2-8. In July 1980, it was decided not to recoat or touch-up the surfaces and to monitor the radome performance until it degraded to that of an uncoated radome.

In early January 1981, the radome deicing heat of all MLS radomes was turned off so that the performance of the radomes could be checked in snow/ice environment. The first test came on 6 January, when a snowfall of 3 inches hit the area with a southerly wind. The Azimuth monitor horn, which faces South, had 0.5 inch of snow; none of the other radomes had any ice or snow build-up. The coating on the monitor horn radome had deteriorated almost completely at this time.

In October 1981, the Basic Narrow radomes were recoated per the schedule shown in Table 2-9. The primers were brushed on and the top coats applied by aerosol spray. Table 2-10 lists the history of these radomes from the date of application through September 1982.

TABLE 2-9. BASIC NARROW RADOME COATINGS

RADOME	RADOME MATERIAL	COATING
Azimuth Scan Beam	Fiberglass	Teflon tape C-tape-36
AZ ID	Fiberglass	ADZ07 primer Aerosol Vellox (blue tint)
OCI (3)	Fiberglass	ADZ07 primer Aerosol Vellox (blue tint)
AZ Field Monitor	Teflon/ Fiberglass	Teflon sheet
EL Field Monitor	Teflon/ Fiberglass	ADZ07 primer Vellox 140 topcoat
Elevation Scan Beam	Fiberglass	ADZ07 primer Vellox 140 topcoat
EL ID	Fiberglass	ADZ07 primer Vellox topcoat

TABLE 2-8. MLS BASIC NARROW SYSTEM AT WASHINGTON NATIONAL AIRPORT (RUNWAY 18) PRIOR TO OCTOBER 1981

Date	Radome	Action (See Note)	Water Repellancy	Months since Initial Application	Months since Last Service	Remarks
4/12/79	All	C	Exc	0	0	ADZ07 primer + Vellox 140
10/09/79	Az,El	I	Good	6.0	6.0	70% of Az surface good, 30% poor. Jet exhaust on El cleaned off.
10/29/79	Az,El	I,T	Fair	6.5	6.5	repellancy Good after touch-up w/Silibond
11/02/79	Az,El	I,T	Fair	6.6	0.1	Repellancy Good after touch-up w/Silibond
11/28/79	Az,El	I,T	Fair	7.5	1.0	Repellancy Good after touch-up w/Silibond
3/17/80	Az	I,T	Poor	11.0	3.5	Repellancy Good after touch-up w/Silibond
4/11/80	Az	I,T	Fair	12.0	1.0	Repellancy Good after touch-up w/Silibond
4/30/80	Az	I,T	Poor	12.5	0.5	Repellancy Good after touch-up w/Silibond
6/03/80	Az	I,T	Poor	13.5	1.0	Executive shutdown. Repellancy Good after touch-up w/Silibond
7/14/80	Az	I	Poor	15.0	2.5	Executive failure. Coating 40% gone.
7/21/80	Az	I	Poor	15.2	2.7	Radome will not be re-coated until coating is gone.
11/14/80	Az	I	Poor	19.0	6.5	Accuracy deviation noticeable during hard rain.
1/06/81	Az	I		20.5	8.0	Snow storm. No snow on radomes; radomes unheated.
	El	I		20.5	14.0	
5/19/81	Az	I	Poor	25.0	12.7	Coating 95% gone.
	El	I	Fair	25.0	18.5	Coating 10% gone.

Note: C Initial coating
R Recoat
I Inspection
T Touch-up

TABLE 2-10. MLS BASIC NARROW SYSTEM AT WASHINGTON NATIONAL AIRPORT (RWY 18) AFTER OCTOBER 1981

DATE	RADOME	REMARKS
28 Oct '81		Following 2 days of rain:
	AZ scan	Beading, no effect on accuracy or ERP.
	Left OCI	Some beading.
	EL scan	No water.
9 Dec '81		All radomes except OCI exhibited high hydrophobicity.
		Teflon radomes beaded.
15 Dec '81	AZ scan	Snow covered the radomes; accuracy and ERP shutdown.
11-15 Jan '82		Sites were inaccessible due to snowfall, but no shutdowns occurred.
23 Jan '82	AZ scan	Ice on radome; accuracy shutdown
8 Mar '82	All radomes	Beading ranged from 80% (brushed Vellox) to 100% (aerosol Vellox and Teflon)
19 May '82	EL scan	Thunderstorms; systems shut down.
21 May '82	EL ID	50% effective.
	AZ scan	Beading, but sheeting does not occur.
	All others	Failed completely.
7 June '82	AZ scan	Displaying no problems with rain.
	EL scan	Coated with Vellox 1828.

2.5.1.2 SMALL COMMUNITY MLS

The radomes were coated initially in August of 1980, using the ADZ07 primer and Vellox 140 top coat. In October 1980, the two monitor horns were recoated using a new primer (ADZ079A) and the Vellox 140 top coat. During the January 1981 snowstorn (referred to in Section 2.5.1.1), only the rear OCI antenna had any snow build-up. The remainder of the antennas, which face in a SSW direction, had no snow or ice build-up.

The radomes were inspected in May and July 1981. The radomes using the old ADZ07 primer had deteriorated significantly, as shown in Table 2-11. The radomes using the newer ADZ079A primer had undergone almost no deterioration. A subsequent inspection in July showed no noticeable changes in any of the radomes. These radomes were also recoated in October 1981; all radomes had a prime coat of ADZ07 and a Vellox finish coat. The history of these coatings is shown in Table 2-12. The primers were applied by brush and the topcoats by aerosol spray.

2.5.1.3 BASIC WIDE MLS

All of the Basic Wide radomes were coated in-plant with Silibond in December 1979 immediately prior to shipping the system to NASA WFC. About 9 months later, the hydrophobicity had significantly decreased on all radomes. Thereafter, all radomes required periodic inspections and touch-up, as shown in Table 2-13.

No additional tests or observations were scheduled for the Basic Wide system after termination of the field support effort.

These radomes were also recoated in October 1981; all radomes had a prime coat of ADZ07 and a Vellox finish coat. The history of these coatings is shown in Table 2-13. The primers were applied by brush and the topcoats by aerosol spray.

TABLE 2-11. MLS SMALL COMMUNITY SYSTEM AT
WASHINGTON NATIONAL AIRPORT (RUNWAY 33)
PRIOR TO OCTOBER 1981

Date	Radome	Action (See Note)	Water Repellancy	Months since Initial Application	Months since Last Service	Remarks
8/23/80	Az, El	C	Exc	0	0	ADZ07 primer + Vellox 140
8/27/80	All others	C	Exc	0	0	ADZ07 primer + Vellox 140
10/23/80	Field mon.	R	Exc	0	0	Previous coating failed. Recoated with ADZ079A primer + Vellox 140
5/01/81	All except field mon.	I	Poor	8	8	No Exec.failures
5/01/81	Field mon.	I	Good	6	6	No Exec. failures
7/15/81	All except field mon.	I	Poor	10.5	10.5	No Exec. failures
7/15/81	Field mon.	I	Good	8.5	8.5	No Exec. failures

Note: C Initial coating
R Recoat
I Inspection
T Touch-up

TABLE 2-12. MLS SMALL COMMUNITY SYSTEM AT WASHINGTON NATIONAL (RWY 33) AFTER OCTOBER 1981

DATE	RADOME	REMARKS
28 Oct '81	All	After 2 days of rain, all radomes clear of water.
10 Mar '82		Water beading over:
	AZ scan, ID	30% of surface
	Rear OCI	75% of surface
	Right OCI	80% of surface
	Left OCI	30% of surface
	AZ Monitor	95% of surface
	EL scan	20% of surface
	EL ID/OCI	60% of surface
	EL Monitor	100% of surface
25 May '82	AZ	Thunderstorms, system shutdown on accuracy (1 occurrence).
	EL	System shutdown every 2-3 minutes.
7 Jun '82	AZ, EL Monitors (2)	Coated with Silibond 1828
1 Jul '82	AZ scan AZ, EL Monitors (2)	Radome completely failed. Radomes OK.
27 Jul '82	AZ scan	Stripped to base material.

TABLE 2-13. MLS BASIC WIDE SYSTEM AT NASA WALLOPS

Date	Radome	Action (See Note)	Water Repellancy	Months since Initial Application	Months since Last Service	Remarks
12/11/79	All	C	Exc	0	0	Coated with Silibond 1828-4A
9/15/80	Az Mon	I	Fair	9.0	9.0	ERP decrease due to heavy dew
	El Mon	I	Poor	9.0	9.0	
9/29/80	Az	T	See Remarks	9.5	9.5	Left half touched up; repellancy of left/right sides exc/good.
	El	T		9.5	9.5	Bottom 1/3 touched up; repellancy of bottom/top parts good/fair
10/02/80	Az Mon El Mon	I,T	Fair	9.5	9.5	Exec shutdown due to ERP. Repellancy good after touch-up
12/11/80	Az	I,R	See Remarks	12.0	2.5	Repellancy on left/right sides was good/fair. Touched-up.
	El	I,R		12.0	2.5	Repellancy on bottom/top was good/fair. Touched-up.
2/02/81	El Mon	T	Poor	13.5	4.0	Exec. shutdown. Touched-up.
2/11/81	El Mon	T	Poor	14.0	0.5	ERP decr. Touched-up.
2/19/81	Az Mon	R	Poor	14.0	4.5	Exec. failure. Recoated.

Note: C Initial coating
R Recoat
I Inspection
T Touch-up

2.5.2 PANEL TESTS

The tests at Washington National included the preparation of a number of coated panels which were placed in the immediate vicinity of the MLS systems. These panels are listed in Table 2-14 and were placed in position on 9 December 1981.

2.6 RF TESTS

Two antenna types were subjected to range tests to determine the RF losses incurred during rain when hydrophobic radomes were used. (Both types are used as field monitor antennas in the MLS system.) The two types were a printed circuit 8-element dipole array and a horn array; the test frequency was 5061 MHz.

The dipole array was tested using conformal radomes (the radome material was applied directly to the PCB material on which the antenna was printed) and a suspended radome (the radome material was separated physically from the PCB material). The horn antenna was tested using the suspended type radome only.

Measurements consisted of measuring the combined antenna/radome gain while being sprayed with water (column 3 in Table 2-15) and after being sprayed (column 4); the measured gain before spraying was used as a reference.

3. WEATHEROMETER TESTING

All testing described so far has been under uncontrolled, ambient conditions. It was realized that a controlled environment could provide meaningful, comparative data. Accordingly, a testing laboratory was retained to run tests on specified coated samples. The report of the testing lab is contained in the addendum. The results of the test are discussed in the next section.

TABLE 2-14. TEST PANELS AT WASHINGTON NATIONAL
(EMPLACED 9 DECEMBER 1981)

BASE MATERIAL	ORIENTATION	COATING	PERFORMANCE 8 MAR 1982
Fiberglass	North	ADZ07 Primer Vellox Topcoat	100% Beading
Fiberglass	North	S048 Primer Vellox Topcoat Laminated	100% Beading
Conolite	North	No Coating	100% Failed (Sheeting)
Fiberglass	North	No Coating	100% Failed (Sheeting)
Fiberglass	East	Silibond 1828	80% Beading
Conolite (Black)	South	ADZ07 Primer Vellox Topcoat	5% Beading 95% Failed
Conolite	South	ADZ07 Primer Vellox Topcoat	80% Beading
Conolite	South	ADZ07 Primer Vellox Topcoat Rolled	75% Beading
Conolite	SSE (by Shelter)	S048 Primer Vellox Topcoat	80% Beading
Conolite	SSE (by Shelter)	ADZ07 Primer Vellox Topcoat Rolled	100% Failed (Sheeting)

TABLE 2-15. GAIN LOSS OF ANTENNAS WITH HYDROPHOBIC RADOMES

ANTENNA	RADOME	LOSS DURING SPRAYING (dB)	LOSS AFTER SPRAYING (dB)
Dipole	Conformal, Tedlar tape	3.7	0.5
Dipole	Conformal, Tedlar tape + Vellox	0.2	0.0
Dipole	Conformal, Teflon (Duroid)	3.5	0.9
Dipole	Conformal, Teflon tape	1.8	0.5
Dipole	Suspended, Teflon fabric, Chem Fab 20R, 2" spacing	2.5	0.3
Dipole	Suspended Teflon fabric, Chem Fab 20R 0.7" spacing	1.5	0.0
Horn	Suspended, Tedlar tape	1.8	0.0
Horn	Suspended, Tedlar Tape + Vellox	0.1	0.0
Horn	Suspended, Teflon/Fiberglass PCB	1.5	0.2
Horn	Suspended Teflon fabric (Chemfab 20R)	1.5	0.2

Initially, 14 test sample types were considered for testing:

1.	Conolite/Tedlar	Uncoated
2.	Conolite/Tedlar	AFC-HMOD-4
3.	Conolite/Tedlar	Teflon film
4.	Conolite/Tedlar	Vellox 1828, brushed
5.	Conolite/Tedlar	Vellox 1828, aerosol
6.	Conolite/Tedlar	ADZ07 primer, Vellox 140, standard spray
7.	Conolite/Tedlar	ADZ07 primer, Vellox 140, pressure rolled
8.	Conolite/Tedlar	S-77 primer, Vellox 140, standard spray
9.	Fiberglass	Uncoated
10.	Fiberglass	Vellox 1828 aerosol
11.	Fiberglass	ADZ07 primer, Vellox 140, standard spray
12.	Teflon fabric	Uncoated
13.	Teflon fabric	Vellox 1828 aerosol
14.	Teflon fabric	ADZ07 primer, Vellox 140, standard spray

The S-77 primer listed with sample 8 was a new formulation that had just been developed by the subcontractor; no previous tests had been run with this primer. As explained in the Addendum, this list was modified slightly before the final samples were selected.

TABLE 2-16

DESCRIPTION OF RADOME MATERIALS & COATINGS

MATERIAL	PRODUCT CODE	DESCRIPTION	MANUFACTURE
AFC HMOD-4		Also referred to as HMOD-4	Lockheed-Georgia Co. Marietta, GA 30063
Conolite		Polyester glass fabric laminate	Plastic laminates 1 Laminate Drive P. O. Box 1973 Morristown, TN 37814
Conolite/ Tedlar		Conolite with Tedlar laminated to one side	
Duroid		Teflon/random glass fibers PC board	Rogers Corporation Chandler, AZ 85224
Fiberglass	TFG	Teflon in fiberglass laminate	
	EFG	Epoxy in fiberglass laminate	
Silibond	1828 1828-3A 1828-4A	Fumed silicon dioxide (FSD)	Silibond Products 25 Industrial Way Wilmington, MA 01887
Fusidox		FSD, early version of Silibond	
Tedlar	PFE150BL30WH	Polyfluoroethylene	E. J. DuPont De Nemours & Co. Wilmington, DE 19898
Tefzel Teflon	200 LZ FEP-200A TFE	Clear teflon	

TABLE 2-16 (CONTINUED)

DESCRIPTION OF RADOME MATERIALS & COATINGS

MATERIAL	PRODUCT CODE	DESCRIPTION	MANUFACTURE
Teflon fabric	100-10R 100-20R 141R	Teflon impregnated fiberglass	Chemfab Material Technologies Division Water Street P. O. Box 476 North Bennington, VT 05257
	CHR-10TB	Teflon impregnated fiberglass	Connecticut Hard Rubber Co. 407 East Street New Haven, CT 06509
Teflon tape (film)	Teflon-FEP film, type A	Teflon tape with adhesive backing	3M Corporation 3M Center St. Paul, MN 55144
Tullan-nox	500	FSD	Tulco Inc. N. Billerica, MA 01862
Vellox	140 1828 1828-3A 1828-4A BC-500 #48	FSD top coats	Clifford W. Estes Co., Inc. Box G Lyndhurst, NJ 07071
	ADZ07 S-048 S-77	Primers for above top coats	

4. DISCUSSION AND RECOMMENDATIIONS

The data to be discussed covers a wide variety of materials and environments over a relatively long time span. The longest test time and largest inventory of materials are offered by the test panels; this data will be discussed in Section 4.1. Following this, the radome field tests will be discussed in Section 4.2 and the weatherometer tests in Section 4.3. The correlation of results between these three sets of tests will be indicated.

4.1 PANEL TESTS

Figure 2-1 shows the results obtained from the 16 Bendix test samples over a 23 month period. One general trend appears: the initial performance level is maintained for a period of 6 to 9 months, then degrades steadily. The single exception is sample 15 which is Silibond 1828-4A on the Conolite/Tedlar sheet; the reason for the exceptional performance of this sample is unknown at this time. The AFC-HMOD-4 (sample 3) started to degrade immediately. The two Teflon coatings (samples 6, 7) had a hydrophobicity less than that of the FSD samples and degradation occurred as with those samples, but the initial hydrophobicity was restored merely by wiping the surface clean with a damp towel. Cleaning of the Silibond/Vellox surfaces had no effect on the hydrophobicity, and it is hypothesized that the granularity of the surface and hence the hydrophobicity decreased with time. *

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*The extremely fine size of the FSD coating and the surface tension of the water combine to cause the droplets to be suspended on the "peaks" of the FSD granules. Thus, there is very little friction and water runoff is rapid, as observed. As the peaks erode, more of the droplet is in contact with the surface, friction increases, and runoff decreases.

The limited snow/ice observations (Table 2-5) support the theory that good hydrophobicity indicates a corresponding resistance to snow and ice. This data indicates again that the Conolite/FSD combination is a superior performer.

With the start of the funded effort, additonal test panels were installed at Bendix (Table 2-6) and Washington National (Table 2-14). These tests supported the conclusions derived above and offered some data. Comparing samples 4, 11, 12, 13 in Table 2-7, leads to the observation that the primer used may have a significant effect on the durability and quality of the hydrophobicity. In these examples, the samples with the S-048 primer were clearly better than those using the ADZ07 primer (although the ADZ07 primer in combination with the microfine Vellox 140, samples 19, performed well). Although a number of different application techniques were employed (brushing, rolling, aerosol, spray gun), the tests were inconclusive in establishing a trend that any one was superior to the others. The tests did indicate a possibility that heavier applications of Vellox (samples 17 through 21) perform better than single or double coats.

The Teflon fabric also behaved as before (samples 5, 6, 7, 8). Although performance degraded, it was restored by wiping the accumulated surface dirt from the panel; the presence of an initial coating of AFC-HMOD-4 made no difference in the end results.

The panel tests at Washington National provide further verification of the above conclusions. All of these involved Vellox on Conolite or fiberglass bases. Within 6 months all of the coatings had either failed or were only partially effective.

To summarize:

a) The base material and primer have an observable effect on the hydrophobicity.

b) FSD is superior to Teflon initially, and both degrade at about the same rate, but Teflon can be restored to its initial hydrophobocity by wiping off surface grime.

c) Application techniques did not appear to be an important factor, although indoor application seemed to give a better and more uniform surface.

In the next section, the radome tests at Washington National will be reviewed, particularly with regard to the preliminary findings listed above.

4.2 RADOME TESTS

Of the three systems used for radome tests, the Basic Wide system at NASA WFC has the least data, due to the remoteness of the site. However, approximately 15 months of data were collected. As seen in Table 2-13, the initial applications lasted no longer than 9 months, then failure developed, as with the test panels, in the form of ERP decrease due to a heavy dew on the radomes. Frequent touchups were performed thereafter by aerosol application, but the hydrophobicity never reached that initially obtained. This may indicate that complete stripping and reapplication of the finish may be preferable to periodic touchups. The NASA WFC airport is located in a non-industrial environment and the usual contaminents present in such an environment were missing. Additionally, the number of flights handled at WFC is significantly less than those handled at Washington National, so that contamination of the radome surfaces by jet blast is unlikely.

The Basic Narrow (BN) and Small Community (SC) systems at Washington National were observed for a period of more than 3 years. This period can be divided into two parts: prior to October 1981 and after October 1981. The relevant data is given in Tables 2-8 and 2-11 and Tables 2-10 and 2-12 respectively for the BN and

SC systems. Each period can be considered separately, since the radomes were recoated in October 1981.

Looking at Table 2-8, all BN system radomes were coated with ADZ07 primer and Vellox 140. The hydrophobicity of the radomes had decreased significantly within 6 months, as might be expected from the above discussions on panel data. Frequent touchups were necessary to maintain the surface to the desired water repellancy. It can be noticed that the AZ radome deteriorated more rapidly than the EL radome, possibly because of its location on a pier that extended into the Potomac River. In this location it was subjected to more moisture and winds than the EL antenna which was located near the runway threshold.

The data for the SC system reflects the same story. Within 9 months after application, the water repellency was rated as poor, although no executive failures were recorded.

In October 1981, the radomes of both the BN and SC systems were retreated. The BN radome coatings are described in Table 2-9, and the performance data in Table 2-10. Of particular interest are the Azimuth scan array and the field monitor that were covered with an adhesive backed Teflon sheet; the remainder had ADZ07 primer plus Vellox. Some of the Vellox had a blue tint which was of help during the application. However, the tinting evidently had a negative effect on the hydrophobicity quality and durability. Correlating the radome coating and performances, the following general conclusion can be made: the Teflon coated radomes permitted some limited water beading and snow collection, but the ooating never did fail completely. The Vellox coated radomes were better initially, but again they were failing in about 6 months by letting sheets of water and heavy beading form on the radomes during heavy rains.

The SC radomes were all treated with the ADZ07 primer and Vellox. Table 2-12 shows that the performance of these radomes

closely parallels those of the BN system in that there is a noticeable drop in water repellency in 6 months.

In summary, the data on the radomes of all three systems agrees with the panel data. The FSD is the superior performer initially, but effectively loses its hydrophobicity in about 6 months. In the next section we will discuss the results of the controlled weatherometer tests.

4.3 WEATHEROMETER TESTS

The laboratory testing consisted of subjecting all samples to the weatherometer in addition to performing limited abrasion and temperature tests on a few samples. The weatherometer data agrees principally with the panel and radome data described above except for one instance; in the weatherometer tests, the Teflon fabric did not perform as well as it did in the panel and radome tests after being wiped clean (panel sample #7 in Table 2-7 is identical to the fabric used in the weatherometer). In all other cases there was good agreement. The FSD sample using the S-77 primer, on which no previous data exists, outperformed all other samples by a wide margin.

The temperature cycling test indicated that no adverse effects should be expected as a result of temperature variations.

4.4 RF TESTS

The results of the RF testing correlate with the panel and radome test results. The Vellox coated radomes provided both a lower maximum and a lower residual attenuation. An additional factor is also evident from the data; the presence of moisture in close proximity to the dipoles, as exemplified by the conformal radomes, had a more severe effect than when the radome was physically separated from the dipole, as with the suspended radomes.

4.5 RECOMMENDATIONS

One of the more critical factors by which a hydrophobic material is to be judged for the MLS application is ease of maintenance. It is desirable that radome coatings have a useful life of at least 12 months and preferably 24 months. The only tested material which meets this criterion is the Teflon fabrics. In cases where there may be an early surface failure due to an extremely high concentration of contaminants in the atmosphere, tests indicate that the hydrophobicity can be restored easily by wiping the surface to remove the accumulated contaminants. Additionally, Teflon is an inert material and will not be affected by airborne chemicals or UV radiation.

The FSD would have been the choice had a longer useful life been demonstrated. Although none of the panel or radome samples indicated such a life, the weatherometer tests showed that a previously untested combination (S-77 primer and microfine FSD) may have a useful life approaching the desired span. This combination is in the process of being field tested at this time. It was applied in mid-August 1982 to the Bendix built MLS system that was installed in Valdez, Alaska in September 1982. Additional applications are planned for the MLS systems at Philadelphia, Pa and Clarksburg, W. Va and for the elevation radomes at Washington National in December 1982.

In view of the above, it is recommended at this time that the uncoated Teflon fabric be used for the internal surfaces of MLS radomes, and that the Field applications of the S-77/FSD be closely monitored and evaluated as a potential replacement for the Teflon fabric.

ADDENDUM

SUBCONTRACTOR FINAL REPORT

FINAL REPORT AUGUST 30, 1982

APPLICATION AND EVALUATION OF HYDROPHOBIC COATINGS AND MATERIALS FOR RADOMES.

PREPARED FOR:

BENDIX COMMUNICATIONS DIVISION
BALTIMORE, MARYLAND

AUTHORITY OF:

FAA CONTRACT DTFA01-81-C-10068
SEPTEMBER 15, 1981

BY:

DAVID T. MINASIAN
M-CHEM CORP.
25 INDUSTRIAL WAY
WILMINGTON, MASS 01887

I. INTRODUCTION

As stated in the Interim Report, February, 1982, the objectives of this project are:

1. To determine from all materials, those which yield the highest hydrophobic performance.

2. To establish durability parameters (useful life) of each material tested by correlating, in accordance with industry guidelines, the hours of accelerated weathering with real life exposure.

3. To compare such data with actual field test data in terms of durability and hydrophobicity in order to determine life expectency.

4. To test the latest developments in formulations and application techniques, with special attention given to the simplification of application techniques.

Also included in the Interim Report was a brief discussion of the dynamics of water film and droplet formation. Since this information is basic to the understanding of hydrophobic phenomena, an extract of this discussion is included in this report, Appendix "A."

This report will describe the laboratory techniques and procedures, as well as present the results of these tests.

In addition, this report will review all field applications and inspections, as well as discuss the most recent developments in formulations and application techniques.

II. SKINNER AND SHERMAN TECHNICAL REPORT

On 5 August, 1982, Skinner & Sherman submitted the last of their findings. A complete copy of this report can be found in Appendix "B."

However, it is appropriate to discuss some aspects of the project before, during and after its completion.

A. Changes in Sample Types to be Tested

The initial inventory of sample types (see Section 3) to be tested as presented in the Interim Report was latered as follows:

Sample Type #10 (Fiberglass furface coated with Vellox 1828 Aerosol) was eliminated due to the extremely poor adhesion of the coating to this surface.

Sample Type #11 (Fiberglass surface coated with Vellox 140 & ADZ-07 Primer) was moved up and designated as Sample Type #10.

Sample Type #12 (Teflon glass reinforced fabric uncoated) was moved up and designated as Sample Type #11.

Sample Type #13 (Teflon glass reinforced fabric) was moved up and designated as Sample Type #12. The coating was a brushing formula of Silibond Aerosol and identified as "Teflon Brushed Silibond."

Sample Types #13 & #14 were two new brushing formulas utilizing Vellox WB-1 & Vellox WB-2-B Carb, respectively. Both Sample Types were applied on Conolite etched Tedlar. The revised inventory of Sample Types is shown on the Skinner & Sherman Lab Report.

B. 200 Hour Exposure Data

The test procedure was established so as to allow for performance evaluation during the conduct of the weatherometer exposure.

Control specimens of each Sample Type (unexposed) were retained, along with specimens taken from the weatherometer at 100, 200, and 876 hour intervals.

After 200 hours of exposure the specimens were evaluated by measuring water adhesion by weight, and contact angle. These specimens which exhibited extreme failure were eliminated from further performance evaluation.

Eliminated were:

- # 1 Uncoated Conolite
- # 2 HMOD-4 on Conolite
- # 7 Vellox Rolled
- # 9 Uncoated Fiberglass
- #13 WB1 (Brushable Vellox)
- #14 WB2 (Brushable Vellox)

Retained for further evaluation were:

- # 3 Teflon Film on Conolite
- # 4 Silibond brushed on Conolite
- # 5 Silibond Aerosol on Conolite
- # 6 Vellox/ADZ-07 on Conolite
- # 8 New Vellox on Conolite
- #10 Vellox/ADZ-07 on Fiberglass
- #11 Uncoated Teflon Fabric
- #12 Silibond Brushed on Teflon Fabric

In addition, the 100 hour specimens from the remaining sample types were evaluated in order to establish a total profile of performance over the entire 876 hours of exposure.

C. Comments Regarding Laboratory Results

The Skinner & Sherman lab tests were completed on 21 July, 1982.

Although the final data provided some very conclusive results over all, certain details appeared to be incongruous, for which no suitable explanation could be given by lab personnel. Some of these details in question are:

1) A strong correlation between water adhesion and contact angle would be difficult to establish. Although in most of the samples, a general increase in water adhesion was observed with a decrease in contact angles, some samples (#6, #7, #13) showed unusually high water adhesion compared to the high contact angles.

Note: Comment was made that water adhesion was noted along the edges of the sample. This water would have been measured along with droplets on the surface. This may have resulted from the method employed in the preparation of the samples. A large sample, usually 10" x 10", was coated and the 2 1/2" x 5" samples then cut from that. Hence, the cut edges would not have been hydrophobically treated and this may have contributed to the variations in correlation between contact angle and water adhesion.

2) Sample #3, uncoated Teflon Film, demonstrated very poor results after 200 hours of weatherometer exposure, evidenced by a low contact angle (44°) and high water adhesion (100 Mg.). However, the 876 hour data demonstrated a more acceptable level of deterioration (95° and 19.2 Mg., respectively). The lab could offer no reasonable explanation for this extreme departure from normal.

3) Except in Sample #8, (New Vellox) and #13 (Brushed Silibond on Teflon fabric), contact angles after 876 hours of exposure showed a normal decrease. In samples #8 and #13, however, contact angle increased slightly.

4) In general, after 876 hours of exposure, all coatings using F.S.D. demonstrated good hydrophobic performance. The contact angle measurements remained at levels suitable enough to be considered super-hydrophobic (+120°).

After 876 hours of exposure, Sample #8 (Vellox New on Conolite) demonstrated both exceptionally low water adhesion (0.3 Mg.) and high contact angle (141°). Sample #12 (Silibond brushed on Teflon fabric) showed some increase in water adhesion but high contact angle (144°). However, of all the F.S.D. coatings tested, Sample #6 (Vellox/ADZ-07 on Conolite) showed the poorest results. This could be compared with field application experience and serve as an effective yardstick in predicting the performance of new F.S.D. based coatings.

III. FIELD APPLICATIONS AND INSPECTIONS

During the fall, winter and spring of 1981-82, field applications and inspections were made on M.L.S. systems at Washington National Airport, Philadelphia International Airport and Benedum Airport, Clarksburg, West Virginia.

In addition, a series of nine test panels were mounted on the pier at Washington National Airport.

In Northern New Jersey, an additional nine panels were mounted in two locations in order to maintain frequent evaluation of these surfaces, especially during periods of rain and ice formation.

Materials used in these field installations have been composed of:

1) Vellox 140 Top Coat over ADZ-07 Primer
2) Vellox 1828 (formerly Silibond 1828) Aerosol & Brush Formulas
3) Vellox 140 Top Coat on S-048 Primer.
4) Teflon Film
5) Uncoated Conolite and Fiberglass (control)

These materials were typical of the developed state of the art in Super Hydrophobic coatings at the time and are not representative of the latest developments and formulations referred to, either in the Skinner & Sherman lab tests or later in this report. A summary of conclusions as a result of periodic inspections follows:

1. The nine test panels at Washington National Airport were experimental panels, each using variations both in formulas and application techniques. These panels failed prematurely, in most cases indicating that no improvements in formulation or application had been made.

2. The V^llox coatings on the M.L.S. radomes at Washington exhibited excellent super-hydrophobic performance initially. The coatings held up well during most of the winter, although showed gradual tendency to bead toward the end of the season. The March 10th Inspection Report indicated considerable beading and an anticipated failure of these coatings within six to eight weeks.

3. The Clarksburg surfaces were inspected twice during the winter and showed excellent super-hydrophobicity during the entire winter and spring. A phone report received in late May indicated slight beading, especially at the outer perimeter of the radomes.

4. The Philadelphia radomes also showed excellent initial super-hydrophobic performance and although they showed a gradual tendency to bead, they did so later in the season, due to the fact that the application was made in December, 1981, two months after Washington.

5. The test panels mounted in two locations in Northern New Jersey were composed of two materials only; both uncoated and coated Conolite. The coating used was Vellox 140 Top Coat over ADZ-07 Primer.

   These coated panels held up well throughout the winter months and began to show beading in late spring with the increase in pollen and dust in the air. A considerable accumulation of debris was evident on these panels by mid-summer, at which time the coated panels were judged to have little or no super-hydrophobic properties.

In general, it may be estimated, as a result of these field tests, that most F.S.D. based coatings of the types developed as of the date of these applications can be expected to maintain acceptable hydrophobic performance for a six to eight month period.

Any significant improvement noted in the accelerated weatherometer tests on new formulations or application techniques, when compared with sample types of coatings used in the field (Vellox 140 on ADZ-07 Primer, for example), should reflect comparable improvement of these new materials in the field. Hence, the extraordinary performance of the New Vellox Top Coat/Primer and the Vellox 1828 Brush Coating, when compared with Vellox 140 on ADZ-07 Primer in the lab tests, seem to indicate that durability has been significantly improved.

Regarding the ADZ-07 Primer, and possible causes of failure, two factors should be considered.

First, the ADZ-07 Primer is, by nature, an extremely tacky surface, formulated to provide the maximum mechanical adhesion of the F.S.D. particles. This tackiness may be a negative factor in outdoor exposure, causing the adhesion of non-hydrophobic contaminents to the surface. The new Vellox primers are non-tacky, although they do exhibit excellent mechanical adhesion during the application process.

Second, fast evaporation of solvents causes sufficient cooling of the surface in high humidity conditions so as to cause condensation. The presence of water on the surface then will interfere with the proper bonding of the F.S.D. particles to the surface. Application should be done at temperatures well above the dew point.

IV. RESEARCH AND DEVELOPMENT

The use of F.S.D. offers the best potential for super-hydrophobic surfaces. The principle of micro-roughness, combined with non-wettable,low energy surfaces, has been demonstrated to yield the highest contact angles obtainable.

The direction of ongoing research in this area is directed toward: 1) Achieving maximum durability by establishing the strongest possible bonds between F.S.D. and the substrate and, 2) Improving and simplifying the method of application.

Specific projects being worked on are as follows:

1) A simple brushable one-part coating capable of being applied by any standard "painting" method.

   An example of this project was a series of one-part brushable coatings identified as BC-500. These products were included in the Skinner & Sherman Test, identified as WB-1 and WB-2. Although they failed completely after 200 hours of exposure, they showed excellent initial performance and are being investigated further.

2) Development of primers as part of a two-part coating system that will both improve the bond of F.S.D. to the substrate and will in themselves be highly adherent to a wide variety of substrates, such as Teflon, Mylar, polyethylene, unprimed metals, etc.

   The New Vellox Sample Type tested in the Skinner & Sherman Lab exhibited outstanding performance using the conventional spray application technique currently used with Vellox/ADZ-07. This primer is in itself a highly water resistant polymer with extremely low water abscrbtion and low conductivity. When combined with the Vellox 140 Top Coat, it has demonstrated extraordinary retention of its hydrophobic characteristics. This primer

shows great promise when used with a brushable Top Coat, greatly simplifying the application technique.

3) Increasing durability by direct application of Vellox 140 Top Coat of plastic substrates, such as Plexiglas, vinyl, polycarbonates, etc.

Recent experiments with the incorporation of F.S.D. directly onto the surface of Plexiglas has demonstrated good durability and extremely high contact angles. Vellox treated Plexiglas may show good potential for M.L.S. monitor antenna faces, as well as radome faces. Plexiglas can be easily molded into complex shapes.

4) Investigation of "factory applied" coatings under controlled conditions to a variety of materials, both rigid and flexible, to eliminate some of the adverse effects of climate (i.e. humidity) present in field application.

For example, successful applications have been made on various fabrics such as Dacron and show promise as lightweight but very strong shrouds used to protect antennas. The complications of both controlling the conditions of applying F.S.D. based coatings, as well as handling large bolts of fabric, require the use of factory facilities.

SUMMARY AND CONCLUSIONS

Throughout the development of the Super-Hydrophobic coatings and surfaces, those surfaces which utilize Fumed Silicon Dioxide have consistently demonstrated the highest performance. Robert Weigand[1] concluded his report with the following statement:

> "Of the coatings tested, fumed silicon dioxide is in a class by itself. After three months it shows good adhesion to polycarbonate and the repellency it offers...is outstanding."
>
> "This material will undoubtedly find wide use in coating radomes for high frequency applications."

In the October, 1979 issue of Microwave Journal[2], Harold Hoffman of Bell Laboratories, Cranford Hill Lab, Holmdel, NJ, published an article titled "Hydrophobic Coating for Antenna Weather Windows." The article describes a test which he conducted using various materials, silicone, Teflon, vegetable base lubricants and F.S.D. based coatings. Each sample was subjectively rated on a scale of 1 to 5 after spraying with water. A rating of 1 described a surface so hydrophobic that the water bounced off. A 3 rating described rivulets and elongated droplets, and 5 described an unacceptable surface which exhibited water sheeting. One of the F.S.D. based coatings (Silibond) maintained the highest rating, dropping only to a rating of just under 2 over the test period.

Other tests described elsewhere in the article show F.S.D. based Silibond as showing droplets, while Teflon, Silicon and vegetable oil based coatings showed complete water films after 69 weeks of testing.

John M. Sayward, in his report for the U.S. Army Corps of Engineers[3], describes specific conditions which are necessary to discourage ice formation and reduce ice adhesion. Throughout the report, Sayward places major emphasis on air occlusion at the substrate/water interface low energy surfaces as necessary phenomenon. Some extracts from Sayward's report follow:

> "5. The attraction of a substrate for ice is directly related to its attraction for water, particularly where hydrogen-bonding is possible. Attraction for water is manifest in determinable properties: contact angle and critical surface tension, which evaluate wettability and adhesion. Determining these should, therefore, guide choice of icephobic surfaces.
>
> 6. Occlusion of air at the interface (due to poor wetting, contamination, surface geometry and low energy surface, i.e. preferential "wetting" by air rather than water), appears generally to be a negative factor in all adhesion.

By interrupting trans-interface exchange of attractive forces, it lowers adhesion bond strength. By creating irregularities for stress concentration, air patches enhance effects of natural or applied stress in initiating or propagating cracks leading to adhesive failure.

7. Ensuring maximum occlusion of air at the interface should produce minimum adhesion. Means for this include provision of: 1) Low energy substrates, 2) Low energy surface contaminants, 3) Air-saturated water or excess air next to the interface, and 4) Optimum geometry of the substrate interface, to maximize θ (contact angle) minimize wetting, and maximum air occlusion and stress concentration."

Although he does not mention F.S.D specifically, and the project did not include specific test results, it is now known that F.S.D. based coatings satisfy both these requirements. Air occlusion is evidenced by the silvery sheen on F.S.D. surfaces, as well as the high contact angles (120° - 140°). The lower contact angles of such materials as Teflon, silicone and the like permit the occlusion of little or no air and are indicative of a higher energy surface compared to F.S.D. surfaces. Sayward summarizes the essential facts concerning low wetting and ice adhesion. Three of his statements are of particular interest regarding F.S.D. based coatings:

1. Contact angle is a valid, and widely accepted measure of wettability, (the highest angle indicating the least wettability).[3]

2. The lower the surface energy and the greater the occlusion of air of the interface, the higher the contact angle[4].

3. "The attraction of a substrate for ice is directly related to its attraction for water."[5]

Since coatings based on F.S.D. have successfully demonstrated the optimum performance by both objective laboratory measurement and subjective observation, it would appear that the use of such coatings are essential in situations where the best performance is required. Although the durability of F.S.D. based coatings may be somewhat less than other coatings (or surfaces), the retention of extremely high contact angles during its useful life indicates that any surface coated properly with these coatings will remain dry and ice free for the period. Furthermore, it should be noted that even in the laboratory results (see appendix), after prolonged weatherometer exposure, the contact angles of most F.S.D. based coatings remained above the contact angles of unexposed Teflon and HMOD-4 surfaces.

Highlights of the history of the development of F.S.D. coatings should also be considered.

1. In 1972, Weigand[6] evaluated results of an F.S.D. coating based on a durability parameter of only 11 1/2 weeks.

2. By 1979, introduction of the Primer/Top Coat Application system demonstrated a slight improvement in durability of just over four months.

3. In 1980-81, continued changes in Primer formulations demonstrated improved durability of six to eight months.

4. The new Vellox Primer, (Sample 8 in the Skinner & Sherman Test) now has demonstrated extraordinary improvement in durability, retaining high contact angles and low water adhesion over the entire 876 hours of weatherometer exposure.

   Although no field installations have been made as yet with this primer, its lab performance, when compared with other F.S.D. coatings which have been exposed in the field, indicates little doubt that life expectancy has been significantly extended.

5. This new primer also shows considerable promise as a base for brushable (rather than spray) Top Coats. Work along this line is being continued.

Hence, when performance becomes the primary consideration, i.e., the necessity of keeping radomes dry and ice-free under the most adverse conditions, F.S.D. based coatings appear to offer the greatest promise of accomplishing this.

FOOTNOTES

[1] Robert M. Weigand, O'Hare ASDE-2 Radome Performance in Rain: Analysis and Improvement, report #FAA RD 73-22, Dept. of Transportation, F.A.A. Systems Research and Development Service, p. 67.

[2] Harold Hoffman, "Hydrophobic Coating for Antenna Weather Windows," Microwave Journal, October 1979, pp. 43-48.

[3] John M. Sayward, Seeking Low Ice Adhesion, Special Report #79-11. U.S. Army Corps of Engineers, Cold Weather Research & Engineering Laboratory, Hanover, NH, April 1979, p. 18.

[4] *Ibid.*, p. 3.

[5] *Ibid.*, p. 12.

[6] *Ibid.*, p. 18.

[7] Weigand, p. 48.

APPENDIX "A"

BACKGROUND INFORMATION

INTRODUCTION

In brief, the purpose of this project is to seek systems which successfully keeps surfaces dry and ice free, and through a series of controlled tests, establish comparative merit and performance parameters for such systems.

In search of such systems however, it is readily apparent that dryness is a relative condition often expressed in such terms as "water resistant", "water proof", "repellant", "hydrophobic" and "super-hydrophobic", all reflecting degrees of dryness ranging from moderate to tatal absence of wetting.

The ability of a surface to resist wetting is the result of the interaction of the physical and chemical structure of the surface itself, and the molecular forces involved in the formation of water droplets.

A concise description of droplet formation follows:

> "The surface free energy arises from imbalance between the interior, where intermolecular forces are mutually satisfied among neighbors, and the exterior, where lack of neighbors leaves some unsatisfied. This leads molecules to seek the interior, minimizing the surface energy and area. Thus a blob of liquid tends to form a spherical drop, the form with a minimum area/volume ratio, and hence minimum free energy...
>
> The drawing together of molecules (as though enclosed in an elastic sheath) produces an apparent surface tensile force called surface tension." (1)

Wetting then occurs when intermolecular forces of a droplet, in proximity of a surface are no longer mutually satisfied and seek satisfaction in the neighboring surfaces, a phenomena known as van der Waals attraction. When wetting is complete and water-to-surface contact is intimate, the surface tension is broken and the intermolecular forces, which once held the droplet in spherical form, are directed to the surface creating a film conforming to the surface.

The surface, (or any compound applied to the surface), which discourages or prohibits to some degree the mutual satisfaction of the molecular forces between the water and the substrate, then contributes to the relative "dryness" of the surface. The fact that various compounds accomplish this in varying degrees is the reason why wettability varies correspondingly.

(1) John M. Sayward, Seeking Low Ice Adhesion, U.S. Army Corp. Regions Res. & Eng. Lab. Hanover, N.H. P.2, 1979.

Can wettability be measured? Yes. In the appearance and behavior of a drop of water on various surfaces, there appears to be a difference in their shape, depending upon the degree of wetting of the substrates. An angle can be formed using the substrate as the base, and a line drawn from the contact point tangent to the side of the droplet. The angle measured inside the droplet expressed in degrees is known as the contact angle. Hence, contact angle is an acceptable expression of wettability and is relatively easy to measure.

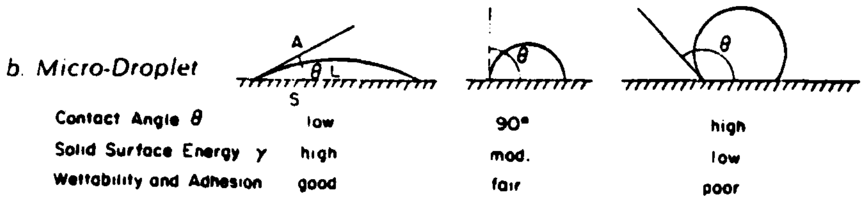

Figure 1
Measurement of contact angle. θ
(Reproduced from: SEEKING LOW ICE ADHESION, ibid P.1)

Surfaces, or coatings, which yield the highest contact angle, are those which allow an air layer to exist at the interface between the substrate and the water, the air layer being the prohibitor of van de Walls forces. A combination of both micro-roughness and a low energy surface provides contact angles in excess of 140° and may be classified as super-hydrophobic. Materials of this class, to be tested are based on Fumed Silicon Dioxide (F.S.D.) and are identified as Vellox 140 and Vellox 1828.

Lower contact angles 90° to 110° classified as repellent or hydrophobic are obtained with Teflon and HMOD-4 and exhibit little or no air at the interface.

APPENDIX "B"

TEST DATA

CLIENT: M-CHEM
25 Industrial Way
Wilmington, MA 01887

Attention: Mr. David Minasian

CASE NO: 15568

REFERENCE: Purchase Order No.

PROJECT DESCRIPTION:

To subject fourteen (14) hydrophobic coatings to weatherometer and performance testing.

SAMPLE IDENTIFICATION:

1 of 12 Six (6) specimens designated "Conolite uncoated"
2 of 12 Eight (8) specimens designated "Conolite H MOD-4"
3 of 12 Eight (8) specimens designated "Conolite Teflon Film"
4 of 12 Eight (8) specimens designated "Conolite Brushed Silibond"
5 of 12 Twelve (12) specimens designated "Conolite Silibond Aerosol"
6 of 12 Sixteen (16) specimens designated "Conolite Vellox ADZ-07"
7 of 12 Eight (8) specimens designated "Conolite Vellox Rolled"
8 of 12 Six (6) specimens designated "Conolite Vellox New"
9 of 12 Eight (8) specimens designated "Fiberglass uncoated"
10 of 12 Eight (8) specimens designated "Fiberglass Vellox ADZ-07"
11 of 12 Eight (8) specimens designated "Teflon, Chem-Fab 100-20R uncoated"
12 of 12 Eight (8) specimens designated "Teflon brushed Silibond B141R"

Above samples received 28 April 1982.

13 Three (3) specimens designated WB-1
14 Three (3) specimens designated WB-2-B-Carb

Above samples received 10 May 1982.

CLIENT: M-CHEM

CASE NO: 15568

METHODS OF TEST:

Weathering Tests

1) Simulated Sunlight and Rain Exposure

All fourteen (14) coating types (3 specimens each) were subjected to accelerated weathering in a Xenon Arc Weatherometer (Atlas Model 60-WR) using a 102 minutes sunshine - 18 minute sunshine and rain cycle.

One specimen of each coating type was removed after 100 hours exposure.

One specimen of each coating type was removed after 200 hours exposure.

The remaining specimens were run to failure (visual examination) or for 876 hours.

2) Freeze/Thaw Cycling

One specimen each of Conolite Silibond Aerosol (sample 5 of 12) and Conolite Vellox/ADZ-07 (sample 6 of 12) were subjected to alternate freezing (approximately -30°C) and thawing (approximately +40°C) conditions. The samples were held at each temperature for one hour before cycling. A total of twenty cycles was carried out.

3) Temperature Extremes Testing

One specimen each of Conolite Silibond Aerosol and Conolite Vellox/ADZ-07 were subjected to a temperature of -50°C for twenty-four hours.

One specimen each of Conolite Silibond Aerosol and Conolite Vellox-ADZ-07 were subjected to a temperature of +70°C for twenty-four hours.

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CLIENT: M-CHEM

CASE NO: 15568

METHODS OF TEST: (continued)

4) Abrasion Resistance Testing (Visual inspection only)

One specimen each of Conolite Silibond Aerosol and Conolite Vellox/ADZ-07 were subjected to Abrasion Testing in accordance with ASTM D968 (Falling Sand Method).

Hydrophobicity

1) Contact Angle of Water Droplets

The contact angle of water droplets (average drop size 0.034 milliliters) on the horizontal test surface was measured by a long focus low power horizontal microscope. Reported results are the average of at least three measurements.

2) Weight of Water Adhering During Simulated Rain

The test specimens were weighed on a Mettler Balance in a test jig which held them at an angle of about 20 degrees from the vertical. Water was added dropwise onto the surface of the specimen on the balance at the rate of 1.5 milliliters in 30 seconds. At the end of 30 seconds the specimen was again weighed. Reported results are the average of three measurements.

Hydrophobicity testing was conducted on the fourteen coating types prior to and after exposure to Weatherometer, Freeze/Thaw Cycling and Temperature Extremes Testing.

CLIENT: M-CHEM

CASE NO: 15568

RESULTS:

WEATHEROMETER TESTING
XENON ARC (102-18 Cam)

Sample Number	Preliminary Visual Examination Before Exposure	Visual Examination 100 hours	200 hours	300 hours
1	Poor surfaces, scratches, shiny spots	No change	No change	No change
2	Scratches	No change	No change	No change
3	Bubbles on surface Brown spot	Increase in size of bubbles Surface mottled	Bubbles Surface mottled	Bubbles Surface mottled Brown spots
4	Scratches, Black specks	Brown stains	Brown stains	Brown stains
5	Scratches, Powdery specks	Brown stains Powdery	Brown stains Powdery	Brown stains Powdery
6	Scratches, Specks	Brown stains	Brown stains Powdery	Brown stains
7	Scratches, Dirty	Brown stains	Brown stains	Brown stains
8	Scratches, Specks Pigment	Powdery	Powdery Brown stains	Powdery Brown stains
9	Scratches, Specks	Yellowing of Surface	Yellowing of Surface, Darker than at 100 hours	Darker than at 200 hours

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CLIENT: M-CHEM

CASE NO: 15568

RESULTS: (continued)

WEATHEROMETER TESTING
XENON ARC (102-18 Cam)

Sample Number	Preliminary Visual Examination Before Exposure	Visual Examination 100 hours	200 hours	300 hours
10	Scratches, Specks Shiny spots	Powdery	Powdery	Powdery
11	OK	Surface Fading	Surface Fading	Surface Fading
12	Not completely coated	Surface Fading	Surface Fading	Surface Fading
13	Scratches, shiny spots	Shiny spots Faded	Shiny spots	Shiny spots Brown spots
14	Scratches, cut in coating	Brown spots	Brown spots Dirty surface	Shiny surface

Specimens 1, 2, 3, 4, 5, 6, 7, 8, 11, 12, 13 and 14 did not exhibit any significant changes from 300 hours to 876 hours.

Specimen 9 continued to darken throughout the remaining 576 hours.

Specimen 10 was removed at 500 hours.

CLIENT: M-CHEM

CASE NO: 15568

RESULTS: (continued)

Sample Identification	Weight of Water Adhering After Simulated Rain (milligrams) Control	200 hrs.	876 hrs.	Contact Angle, degrees Control	200 hrs.	876 hrs.
1) Con. Uncoated	20.8	94.0	*	90	50**	*
2) Con. HMOD-4	0.0	48.8	*	96**	65	*
3) Con. Tef. Film	0.0	111	19.2	101	44	95**
4) Con. Silibond Brush	0.0	13.8	3.7	139	100	139
5) Con. Silibond Aerosol	0.0	23.3	5.8	131	111	128**
6) Con. Vellox/ADZ-07	0.0	46.3	~~*~~ 28.7	142	121	121 ~~*~~
7) Con. Vellox Rolled	3.5	70.7	*	132**	112	*
8) Con. Vellox New	0.0	2.2	0.3	130**	135	141
9) F.G. Uncoated	27.7	79.8	*	91	39	*
10) F.G. Vellox/ ADZ-07	0.0	2.5	8.3 (500 hrs.)	151	127**	132 (500 hrs.)
11) Teflon Uncoated	8.3	14.7	71.7	97	94	91
12) Silibond Brush B141R	0.0	6.5	8.7	132	120	144
13) WB1	*	164.7	*	*	137	*
14) WB2	*	82.7	*	*	74**	*

After Temperature Testing

Sample Identification	Weight of Water Control	Contact Angle Control
5) -50°C 24 hr.	1.5	150
5) +70°C 24 hr.	1.5	152
5) 20 Freeze/Thaw cycles	0.0	150
6) -50°C 24 hr.	0.0	149
6) +70°C 24 hr.	0.2	150
6) 20 Freeze/Thaw cycles	0.0	142

* Not tested per client instructions

** These samples showed a higher than normal point to point variability in contact angle. Reported value is average of six measurements.

CLIENT: M-CHEM

CASE NO: 15568

RESULTS: (continued)

Abrasion Resistance

ASTM D968 Falling Sand Method

Liters of Sand	5. Conolite Silibond Aerosol	6. Conolite Vellox/ADZ-07
50	Beginning to wear	---
60	Increase in wear	---
70	Increase in wear	---
80	Increase in wear	---
90	1/4" diam. circle wear pattern (test discontinued)	---
100	---	No visible signs of wear Test discontinued

Note: Due to the configuration of the substrate (weave pattern) accurate thickness measurements could not be made.

Respectfully submitted,

SKINNER & SHERMAN LABORATORIES, INC.

H. Haldean Dalzell

Haldean Dalzell, Ph.D.
Laboratory Manager

HD/car

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CASE NO. 15568
ADDENDUM

skinner & sherman laboratories inc.

A25

New England Laboratories

300 SECOND AVENUE, P.O. BOX 521, WALTHAM, MASSACHUSETTS 02254 • 617-890-7200

05 August 1982

CLIENT: M-Chem
25 Industrial Way
Wilmington, MA 01887

Attention: Mr. Thomas Kell

CASE NO: 15568 - Addendum

REFERENCE: Per your request

PROJECT DESCRIPTION:

To conduct additional performance testing on selected hydrophobic coatings.

SAMPLE IDENTIFICATION:

1 of 12 - Six (6) specimens designated "Conolite Uncoated".
2 of 12 - Eight (8) specimens designated "Conolite H MOD-4".
3 of 12 - Eight (8) specimens designated "Conolite Teflon Film".
4 of 12 - Eight (8) specimens designated "Conolite Brushed Silibond".
5 of 12 - Twelve (12) specimens designated "Conolite Silibond Aerosol".
6 of 12 - Sixteen (16) specimens designated "Conolite Vellox ADZ-07".
7 of 12 - Eight (8) specimens designated "Conolite Vellox Rolled".
8 of 12 - Six (6) specimens designated "Conolite Vellox New".
9 of 12 - Eight (8) specimens designated "Fiberglass Uncoated".
10 of 12 - Eight (8) specimens designated "Fiberglass Vellox ADZ-07".
11 of 12 - Eight (8) specimens designated "Teflon, Chem-Fab 100-20R Uncoated".
12 of 12 - Eight (8) specimens designated "Teflon Brushed Silibond B141R".

The above samples were received on 28 April 1982.

Sample 13 - Three (3) specimens designated WB-1.
Sample 14 - Three (3) specimens designated WB-2-B-Carb.

The above samples were received on 10 May 1982.

TECHNICAL REPORT

05 August 1982

CLIENT: M-Chem

CASE NO: 15568 - Addendum

RESULTS OF ADDITIONAL TESTS:

Sample Identification	Weight of Water Adhering After Simulated Rain (milligrams)		Contact Angle, degrees
	100 hours	876 hours	876 hours
1. Conolite Uncoated	----	----	----
2. Conolite H MOD-4	----	----	----
3. Conolite Teflon Film	23.7	----	----
4. Conolite Silibond Brush	9.8	----	----
5. Conolite Silibond Aerosol	1.7	----	----
6. Conolite Vellox ADZ-07	----	28.7	121
7. Conolite Vellox Rolled	----	----	----
8. Conolite Vellox New	0.3	----	----
9. Fiberglass Uncoated	----	----	----
10. Fiberglass Vellox ADZ-07	0.0	----	----
11. Teflon Uncoated	33.7	----	----
12. Teflon Brushed Silibond B141R	2.2	----	----
13. WB-1	----	----	----
14. WB-2-B-Carb	----	----	----

Respectfully submitted,

SKINNER & SHERMAN LABORATORIES, INC.

Haldean Dalzell

Haldean Dalzell, Ph.D.
Laboratory Manager

HD/ls

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